Micro-factory for Submerged Assembly: Interests and Architectures

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***Abstract*— The development of new hybrid microsystems needs new technologies which are able to perform assembly of small micro-objects. Now, the current micromanipulation technologies are still unreliable for micro-objects which typical size is down to hundred micrometers. Consequently, the study and the development of innovative artificial micro-object manipulation strategies in these dimensions are particularly relevant. As presented in the literature, micromanipulations are perturbed by the adhesion and surface forces which depend on surrounding mediums. We propose to perform micro-assembly tasks in liquid medium, because adhesion and surface forces applied on submerged micro-objects are less important than in air. An overview of the micro-forces in air and in liquid is presented in this paper.**

This paper focuses on the architecture of a submerged assembly cell including the definition of stocks, conveyance systems and workstations. Defining the architecture of the submerged assembly cell is indeed a keypoint of the cell design. The stocks and workstations could be for example place in a large unique liquid medium or in a collection of droplets.

Transfers of micro-objects in the submerged assembly cell may be obtained by: (i) moving the micro-objects in an unique liquid medium; (ii) moving the micro-objects through the air from one to another liquid medium; (iii) transfert of micro-objects by movement of the liquid bowl. The analysis of the combination of different transfer types allows the construction of the typical architectures of assembly cell for submerged medium.

I. Introduction

The development of micro-assembly technologies requires reliable and automatic micromanipulations methods and technologies. For objects of which typical dimensions are below the limit of 100 micrometers, in most of cases, the surface forces are greater than the volumic forces, and the automation of micromanipulation tasks under this scale limit is particularly difficult. Surface forces are a function of the medium physical parameters like pressure, temperature, and humidity, so an automatic micromanipulation under 100 micrometers typically needs to control these physical parameters. The usual solution is to perform micromanipulations in a controlled chamber [1]. An other solution to increase the efficiency of the micromanipulations is to carry out them in a submerged medium. The use of a submerged medium is able to reduce interaction forces, adhesion forces and electrostatic perturbations [2].

To model, analyse and test new submerged micro-objects manipulation strategies and innovative assembly technologies, a three years research project (called *PRONOMIA* project) supported by the french National Research Agency ANR started in December 2005. The final goal is to develop an experimental prototype able to perform assembly tasks of micro-objects which typical dimension is less than 50 micrometers in a liquid medium. This research project is studying: (i) modelling of the submerged micro-world and definition of new micromanipulation strategies; (ii) definition of the assembled micro-objects and submerged assembly cell architecture; (iii) the force and visual feedback during micromanipulation and the automatic control strategies; (iv) definition of a microfactory modular architecture with standard interfaces.

This paper focuses on the definition of the elementary assembly cell elements and architectures. We present in a first part a comparison between surface forces, contact force and hydrodynamic force in air and in liquid to exhibit the potential interest of liquid medium in micromanipulation. The definition of the architecture of the assembly cell in submerged medium is discussed in the last part.

II. Submerged Micro-assembly Interest

Although our approach concerns liquid medium in general, this part is focused on the comparison between air and water. The behavior of micro-objects is dominated by surface, contact and hydrodynamic forces rather than volume based forces. The comparative analysis of these forces as a function of the medium (air or water) is developed in three parts. First, the impact of the medium on surface forces like electrostatic, van der Waals and capillary forces is presented. In case of water, hydrophobic, steric and double-layer forces have to be considered too. Secondly contact forces modellings by pull-off force in air and in water are compared. Finally the hydrodynamic effects on micromanipulations are discussed.

A. Surface Forces

1) van der Waals Forces: The van der Waals forces are well known atomic interaction forces. For an interaction between a plane (1) and a spherical object (2), they are equal to:

$$F_{vdw}(D) = -\frac{A_{12}R}{6D^2} \tag{1}$$

where A_{12} is the Hamaker constant of the interaction (1-2), D is the distance between (1) and (2) and R is the radius of the spherical object (2).

For interaction of two materials in the presence of a third medium (3), the total force F_t to consider is expressed by the extended DLVO theory (XDLVO) proposed by Xu and Yoon [3], [4]:

$$F_t = F_{vdw} + F_{dl} + F_h \tag{2}$$

The total force is the sum of the van der Waals forces, the double-layer force and a third term which represents all other forces such as solvation, structural, hydration, hydrophobic, steric, fluctuation forces, etc. The three terms are expressed as follows:

- The van der Waals force in a third medium (3) is a function of the Hamaker constant denoted A_{132} estimated by:

  $$A_{132} = A_{12} + A_{33} - A_{13} - A_{23} \tag{3}$$

  The liquid medium can induce a diminution of the van der Waals force from 50% to 98% [5], [6], [7].
- The repulsive double layer force F_{dl} can be currently written as [8], [9], [10]:

  $$F_{dl} \simeq 4\pi R\epsilon_3\kappa_3\Phi_1\Phi_2 e^{-\kappa_3 D} \tag{4}$$

  where ϵ_3 is the dielectric constant of the medium, Φ_1, Φ_2 are the surface potentials of both sphere and surface and κ_3 the Debye length of the medium. The repulsive double layer force F_{dl} is typically greater than the van der Waals force for distance D between $D = 1\,nm$ and $D = 10 - 20\,nm$ [8]. In this range, this repulsive force is able to reduce van der Waals force's impact.
- The third term represents notably the solvation forces which have typically significant impact at very small range lower than $10\,nm$. In water, these force is repulsive for hydrophilic surface and attractive for hydrophobic surface [8]. Thus an hydrophilic surface is able to reduce the impact of the van der Waals force.

The immersion is then able to globally reduce the interaction forces.

2) Electrostatic Forces: The force applied by an electrostatic surface (σ_1 surface charge density) on an electric charged particle (q_2) is given by:

$$F_e = \frac{q_2\sigma_1}{2\epsilon_3} \tag{5}$$

The water dielectric constant ϵ_3 is of higher magnitude than the air dielectric constant. So, in the same electrical charges configuration (q_2, σ_1) electrostatic force is significantly reduced in water.

Moreover electrostatic perturbations observed in micromanipulation are caused by tribo-electrification. During a micro-assembly task, friction between manipulated objects induces electric charges on the objects surface. The charges density depends on the tribo-electrification and conductivity of the medium. Effectively, a higher electric conductivity medium is able to discharge objects' surfaces. Water, especially ionic water, has better electric conductivity than air. Consequently, charges density in water is reduced. The electrostatic force directly proportional to the charge density σ_1 is therefore reduced.

Both impact of the immersion on electric properties of the medium (dielectric constant and conductivity) induces a reduction of electrostatic forces. In conclusion, electrostatic perturbations are highly reduced in water compared to the air.

3) Capillary Forces: The capillary phenomenon between an object and a substrate in air can be described by a liquid bridge between both elements. This capillary force is directly a consequence of the interface between the liquid and the air near to the object. In a liquid this surface disappears, so this force is cancelled in a liquid medium.

B. Contact Forces

The pull-off force represents the required force to break the contact surface between two objects. In case of a sphere (radius R) in interaction with a planar surface, pull-off force F_{PO} is approximately given by following contact models: JKR [11] for the lower boundary or DMT [12] for the higher boundary:

$$\frac{3}{2}\pi R W_{12} \leq F_{PO} \leq 2\pi R W_{12} \tag{6}$$

where W_{12} is the work of adhesion between both objects (1) and (2). In air, the work of adhesion is expressed by:

$$W_{12} \simeq 2\sqrt{\gamma_1\gamma_2} \tag{7}$$

where γ_1, γ_2 are the surface energy of the objects 1 and 2.

In case of objects submerged in a medium (3), the surface energy, called W_{132}, required to separate two objects (1) and (2) submerged in a medium (3) is given by:

$$W_{132} = W_{12} + W_{33} - W_{13} - W_{23} \tag{8}$$

For example, in case of a SiO_2-SiO_2 contact ($\gamma_{SiO_2} = 290\ mJ.m^{-1}$ [13]), the theoretical surface energies in air and in water are (from (7), (8)):

$$W_{12} = 580\ mJ.m^{-1} \quad W_{132} = 146\ mJ.m^{-1} \tag{9}$$

In this example, the pull-off force is reduced in water compared to the air. Usually, solid state surface energy are around $1000\,mJ.m^{-1}$ and the theoretical pull-off reduction is around 50% to 80%.

C. Impact of the Hydrodynamic Forces on the Micro-objects Behaviour

In case of a micro-object placed in an uniform liquid flow, the Stokes law directly gives the hydrodynamic force applied to an object in a uniform flow of fluid defined by a dynamic viscosity μ and a velocity V:

$$\overrightarrow{F}_{drag} = -k.\mu.\overrightarrow{V} \tag{10}$$

with k a function of the geometry

eg: $k = 6\pi R$ in case of a sphere - radius R

This law is valid when the flow Reynolds number is lower than 1. As the dynamic viscosity μ is significantly higher in a liquid than in the air, the hydrodynamic force highly increases in a submerged medium.

As inertial effects are very small in the micro-world, micro-objects acceleration is usually very high. In this way, micro-objects velocity is able to increase in a very short time and object trajectory could be difficult to control especially in case of visual feedback. A liquid medium which induces high hydrodynamic force is able to reduce maximal micro-objects velocity [14] and thus significantly reduces the micro-objects losses out of the working area.

D. Synthesis

In conclusion, contact, non contact and hydrodynamic force were presented in both liquid and dry media. This analysis shows the reduction of contact and non contact forces in a liquid compared to the air. As these effects are able to perturb the micromanipulation tasks, the use of a liquid could improve the micromanipulation efficiency. Moreover, hydrodynamic effects are beneficial to the micro-objects behaviour during their micromanipulation. Thus, the theoretical study shows the interest of submerged media for such tasks. Comparisons of force measurement in both air and water, and experimental microgripping tests were performed as presented in [2].

Consequently, we propose to build a micro-assembly cell where assembly tasks are performed in a liquid medium. This approach will allow the assembly of micro-objects whose typical size is lower than 50 micrometers. Applicative interests are notably focused on assembly of hybrid MEMS/MOEMS composed of different composants which have (micro)fabrication incompatibilities (optical components on a Silicon microsystem for example).

III. Assembly Cell Architectures

The goal of the submerged assembly cell architecture is to define the type of stocks, conveyance systems and workstations. We assume that the input of the micro-assembly is considered as a stock of micro-objects (called start stock). Its output is assembled micro-products composed of two or more micro-objects (called final stock).

The suitable definition of the cell architecture is a keypoint of the cell design. For example, the architecture could be defined as a large liquid medium which contains all stocks and workstations (see case (a) in Fig. 1) or as a collection of droplets each devoted to one workstation or one stock (see case (b) in Fig.1).

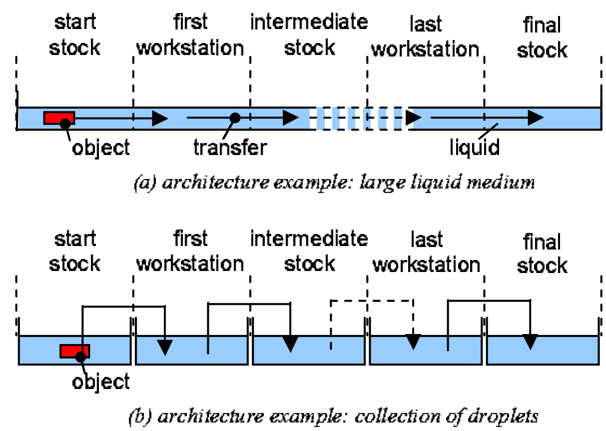

Fig. 1. Examples of Submerged Assembly Cell Architectures

In this section, the design of the start stock is first defined. Secondly the assembly cell elements (stocks and workstations) are described. Finally assembly cell possible architectures are discussed.

A. Start Stock

As sticking effects may appear between micro-objects, bulk stocks will not be considered. As the micro-objects have typical dimensions lower than 50 micrometers it seems impossible to manually manipulate it. So, we propose to stock the object fixed on a millimetric part. Each millimetric part containing its micro-objects is called "cluster of micro-objects". Consequently the feeding of the micro-assembly cell can be done manually.

The cluster has to have dimensions around the millimeter: a compromise between the size of the cluster and the easiness of the manual manipulation has to be found.

1) Definition of the Cluster of Micro-objects: The physical link between the millimetric part and the micro-objects can be obtained with various technologies:

- A sacrificial layer where the release is obtained by chemical machining.
- A non-contact force like electrostatic or magnetic forces where the release is induced by the cancellation of the force field.
- A mechanical breakable link where a high mechanical constraint in the link induces the release.

The first solution does not allow to select one and only one object for release. Cancellation of sacrificial layer could induce the release of a large number of micro-objects. Moreover, the chemical attack may require some rinsing which is very difficult to achieve without inducing the lost of the released objects [15].

The second solution could guarantee a selective release of one micro-object. However, this solution needs the development of a complex device to control force field. Moreover, the micro-objects need to have specific magnetic or electric behavior.

The third method seems to be the more appropriate and simple solution. In fact, this solution is compatible with a selective release and does not require specific magnetic or electric properties. The release can be achieved by applying a force on the breakable link or on the micro-objects by a microtip. Moreover, as the release is performed in liquid, the high acceleration of the micro-objects after link break does not induce its loss out of the working area.

According to this analysis we choose the third solution.

2) Nature of the Cluster of Micro-objets: Two types of clusters could be designed:

- Clusters devoted to products which contain all the components of the final product. Micro-objects are stocked in kit form and the assembly tasks require only one cluster. All the components of an assembled microproduct have to be fabricated in the same cluster with compatible microfabrication technologies. Each cluster is devoted to one microproduct.
- Clusters devoted to components which contain a few types of components. The assembly tasks requires several clusters and each cluster can be used for different final products. This solution allows the assembly of micro-objects fabricated with incompatible microfabrication technologies (hybrid assembled microsystems).

The first solution has the lowest modularity, and does not allow to produce hybrid microsystems. Consequently, we choose the use of clusters devoted to components.

B. Micro-assembly Cell Elements

1) Workplaces and Stocks: Assembly of micro-objects placed initially in clusters requires two steps:

- Micro-objects release from the cluster and
- the assembly.

Both steps have different constraints: the release task requires a high force (typ. mN), and a coarse precision (typ. 10 μm) contrary to assembly which requires small force (typ. nN) and fine precision (typ. up to 1 μm). Consequently, it appears that both operations have to be performed in two different workstations, with two specific micromanipulation systems.

Consequently the assembly cell will contain a start stock of clusters, a release workstation, an intermediate stock, an assembly workstation and a final stock of assembly products. The start stock is a manually made stock of millimetric clusters. Adhesion effects can be neglected on cluster, so the start stock can be placed in air or in liquid. With the exception of the start stock, the other places require micro-objects manipulation and have to be performed in the liquid medium to reduce adhesion perturbations.

2) Cluster Transfer: The transfer from the start stock to the release workstation is called 'cluster transfer'. As the size of the liquid medium (typically greater than the capillary length: 2.7 mm) greatly exceeds the size of a cluster (typ. 500 micrometers), two strategies can be used:

- Displacement of the required cluster form the stock to the release workstation,
- displacement of whole stock to the release workstation.

In the first case, the transfer system has to be able to catch a cluster, to position it in the release workstation, and to transfer it back to the stock after object release. This solution requires the development of a complete micromanipulation transfer system which is able to catch and position a cluster in both stock and release workstation.

In the second case, the transfer system has to move the whole stock in the release workstation without release it. This solution requires only a motorized stage to generate the stock movement. Considering this technological facility, this last solution is retained. The interest of this solution is a direct consequence of scale effects on production engineering: In microscale it can be easier to transfer the whole stock comparative to the individual transfer of a each stocked piece.

C. Micro-assembly Cell Architectures

The different cell architecture is defined as a combination of the transfer modes.

1) Transfer Modes: Between stocks and workstations, micro-objects transfers have to be developed. The transfer of a micro-object from one submerged place to another one can be performed through different ways:

- Direct transfert of micro-objects in the liquid medium (figure 2(a));
- Direct transfert of micro-objects through the air from one to another liquid medium (figure 2(b));
- Indirect transfert of micro-objects by macroscopic movement of the liquid bowl (figure 2(c));

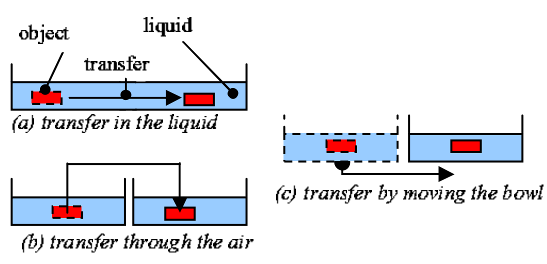

Fig. 2. Transfer Types

2) Different Architectures: The combination of the previously described transfer modes allows the systematic construction of the architectures solutions. All architectures were then studied. Some of them lead to technological incompatibilities. For example, in the case presented in figure 3, cluster transfer inside the liquid cannot be followed by moving the bowl to the intermediate stock. In fact, it would transfer the whole start stock to the intermediate stock. After exclusion of technological incompatibilities, 28 solutions are available.

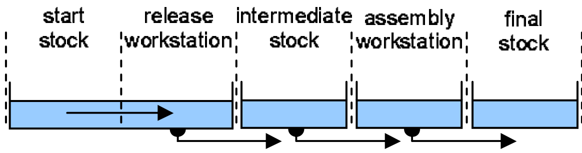

Fig. 3. Absurd Architecture Example

D. Architectures Analysis

The choice of the right configuration requires some criteria:

- reducing the technological complexity (degrees of freedom, etc.)
- modularity,
- controlling the medium composition at each workstation,
- liquid renewal

The transfer through the air requires a lot of degrees of freedom and induces a potential contact between the object and the air. Consequently, we choose to reduce the number of transfers through the air.

The only one architecture which does not require any transfer through the air is the case ‘A’ in the figure 4. In this solution, all stocks and workstations take place in the same liquid. However, this solution has two major drawbacks:

- incapacity to control independently liquid medium properties in workstations and stocks;
- no liquid renewal.

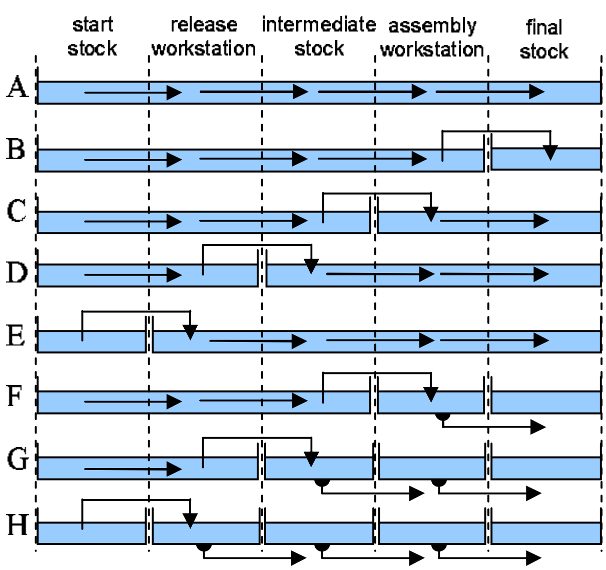

Fig. 4. Architectures Which Contain a Maximum of One Transfer Through the Air.

The solutions which require only one (or less) transfer through the air are also described in figure 4. Two types of cases are given:

- The cases ‘B-C-D-E’, where the transfers are performed in the liquid excepted for one;
- the cases ‘F-G-H’, where the transfers are performed in the liquid before a transfer through the air, and are performed by bowl movement after.

As the first transfer (i.e. between start stock and release workstation) is a transfer of millimetric clusters, it is easier to perform this cluster transfer in the air than the others. Consequently cases ‘E’ and ‘H’ are interesting solutions. Moreover these two cases are the most modular because all transfers of micro-objects are identical (micro-objects transfer in the liquid in case ‘E’ and micro-objects transfer by moving the bowl in case ‘H’). Finally it could be important to control chemical medium composition at each step (stock and workstation). Consequently, the case ‘H’ where chemical composition can be controlled independently in each step seems to be the best architecture.

IV. Conclusion

The submerged liquid is an original and relevant way to perform micro-assembly tasks of micro-objects whose typical size is lower than 50 micrometers. The interest of this approach was discussed and microforces comparison in air and liquid was presented. A keypoint of the design of an assembly cell for submerged micro-assembly is the definition of its elements and its architecture. The design of the stocks was discussed and typical architectures of submerged micro-assembly cell was presented.

Acknowledgment

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